The implications of maritime vessel traffic, wetted surface area and port connectivity for hull-mediated marine bioinvasions on the U. S. West Coast

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Executive Summary

Commercial shipping is an important transfer mechanism (vector) for non-native species in coastal marine ecosystems. Ships move aquatic organisms in ballast tanks or on the outer hulls (including a variety of exposed underwater surfaces). As a contemporary vector for species transfers, ballast water (BW) has received much more attention than hull biofouling, especially in the United States. As a critical step toward assessing the scope of hull fouling as a vector along the U. S. West Coast, we conducted an analysis of shipping patterns and estimated the magnitude of underwater hull surface (wetted surface area, WSA) arriving to California, Oregon, and Washington ports. Our analysis was based on a recent two-year period (July 2003 - June 2005). Using the specific dimensions of each arriving vessel, we calculated the WSA, providing a measure of potential colonizable area for biofouling organisms (analogous to discharge volumes for the BW vector). These results were summed to examine flux of WSA by vessel type and arrival port.

A total of 29,282 vessel arrivals were recorded to West Coast ports over two years, having an estimated WSA of 265.6 million m^2. Ships arriving from overseas (i.e., with a last port-of-call outside of the three western states) accounted for approximately two-thirds of the traffic, and one-third of arrivals were from coastwise voyages (with a domestic last port of call). Vessels arrived from ports located around the globe, but most overseas arrivals came from the strongest trade links with Asian ports in the NW Pacific and from Alaska, British Columbia and Mexico in the NE Pacific.

Overall, containerships dominated both arrivals and WSA patterns, contributing more than other ship types. There were also differences among ship types in terms of mean WSA, frequency of arrival, voyage routes and destination ports. These differences may be especially relevant to hull fouling transfers of NIS because of the external nature of the vector. In addition, the magnitude of coastwise traffic highlighted the connectivity among West Coast estuaries, linking source and destination ports and creating opportunity for the spread of non-native organisms by ships. Models of maritime transport geography may prove useful for assessing and predicting hull fouling transfers

of species. For example, the pendulum model of shipping, where ships traverse an ocean followed by several shorter trips to coastwise ports before a returning transoceanic voyage, fits West Coast containership traffic well. Along with domestic coastwise traffic, this may have implications for the secondary spread of NIS – particularly from San Francisco Bay, which is the most invaded bay in California, Oregon and Washington.

Three general aspects of shipping may have inadvertently reduced the risk of invasions from hull fouling on the West Coast and elsewhere: use of antifouling coatings, containerization of cargo, and use of riverine ports. Antifouling coatings reduce biofouling accumulation, fuel consumption (drag) and hull maintenance, thereby reducing the likelihood of non-native species transfer. Containerization of cargo has resulted in shorter residence time in ports and faster sailing speeds, decreasing opportunities for colonization of hulls in ports and persistence on hulls (respectively). Use of river ports exposes organisms to freshwater and marine water, causing mortality of some organisms due to rapid salinity changes and reducing the likelihood of transfer and colonization.

Despite such historical aspects of shipping that may reduce invasion opportunity, the magnitude of these effects and also the biota associated with modern vessels remains poorly understood. While we have characterized the magnitude of WSA flux for the West Coast by vessel type and port system, the proportion of hulls colonized and the species diversity remain unknown at the present time.

It is clear that invasions are resulting from hull fouling of ships, and this vector may rival ballast water, especially for coastwise transfers. Management options, if required, are not straightforward however, because data are lacking. Current management in other regions of the world is focused on stochastic occurrences, targeting vessels with limited husbandry and high port residence as a proxy for high-density hull fouling. While there is a solid rationale for this approach, it also includes a minute fraction (<1%) of all arrivals, and invasion risk associated with most vessel arrivals has not been characterized. An assessment of biofouling by vessel type and operation, as well as estimating associated rates (risk) of establishment, is a critical gap and priority for informing effective policy, to both minimize transfers of non-native species by ships' hulls and to protect natural marine and freshwater resources of Pacific states.

THE IMPLICATIONS OF MARITIME VESSEL TRAFFIC, WETTED SURFACE AREA AND PORT CONNECTIVITY FOR HULL-MEDIATED MARINE BIOINVASIONS ON THE U. S. WEST COAST

List of Figures

List of Tables

Introduction

As the primary agent of marine bioinvasions on a worldwide scale, patterns in maritime shipping are pivotal in the study of marine vector ecology. Major studies of nonindigenous assemblages at numerous scales around the world, from individual harbors to regions to whole coastlines, consistently point toward shipping as a dominant vector behind a majority of initial species incursions (Eno et al., 1997; Cohen & Carlton, 1995; Cohen et al., 1998; Ruiz et al., 2000; Hewitt et al., 2004;). Shipping has also enabled numerous secondary invasions and subsequent spread, providing nonindigenous species (NIS) with a transfer mechanism for previously unattainable range increases (Apte et al., 2000; Ruiz et al., 2000). The scale of its geographical reach and its historical importance, dating as far back as the earliest civilizations, means the impact of shipping on global biogeography has been profound. There are few reasons to suggest that this impact will not continue to be formidable in the future, especially given the increasing scale and tempo of global trade that relies primarily on commercial shipping.

A better understanding of the geography of maritime trade, and its implications for species introductions, may allow managers to effectively employ vector management strategies that stem the flow of NIS and protect native biodiversity. It would certainly contribute significantly to researchers' predictive abilities. In addition, the mechanisms of shipping – such as how different cargoes require different vessel types, vessel behaviors, trade routes and port requirements – provide a proxy measure of vector variability that offers added insight into how species are moved around by ships and why their fate may be determined by shipping patterns.

Analyses of many facets of marine bioinvasions point to some important trends: 1) the rate of coastal introductions appears to be increasing rapidly in regions with good baseline data; 2) ships are a dominant vector for many global regions, when compared to all other vectors combined; 3) shipping is increasing in terms of numbers, sizes, speeds, and voyage routes; and 4) control and eradication as management options are difficult and expensive at best, at worst they are nearly impossible, meaning prevention is widely deemed the best option.

Although the role of commercial shipping in coastal invasions is clearly pronounced, this results from a combined effect of transfers in the ballast tanks of ships and on the hulls (and other underwater surfaces). Of these two sub-vectors, ballast water has received the most profile in the United States, being associated with such high-impact invasions as the Eurasian zebra mussel *Dreissena polymoprha* in the Great Lakes and the Asian clam *Corbula amurensis* in San Francisco Bay (Roberts, 1990; Nichols et al 1990). However, it is important to recognize that both ballast water and hull fouling are responsible for aquatic invasions, and their relative contributions to the total number of ship-mediated invasions is not presently known (Fofonoff et al. 2003).

Maritime trade and introductions on the U. S. Pacific Coast

Over the course of millennia, shipping has been a dynamic force in global transport geography. Changes in scale, materials and technology, and the types of commodities being shipped brought about its dynamism. Examples of major shifts include the switches from sail to self-propulsion, wooden to steel hulls, growth of shipping routes from regional to global scales, and the reduction in passenger transport by sea. Dramatic shifts have continued to occur over the past four and a half decades that have played a central role in the growth of international trade. Containerization was significant among the reasons for these shifts, which altered the scale of ships and shipping and allowed for efficient intermodal transport of goods (Helling & Poister, 2000). This shift has happened in tandem with the trend toward globalization of international trade; both may prove to have significant impacts (positive and/or negative) on patterns of organism translocation and species introductions.

A body of evidence exists that indicates how species assemblages have been transferred between regions that have strong maritime trade links (Eno et al., 1997; Ruiz et al., 2000, Hewitt et al., 2004). On the U. S. West Coast, this has manifested itself in the numbers of species that have probably been brought by ships from the NW Pacific to bays and harbors in California, Oregon and Washington (Carlton & Geller 1993; Cordell & Morrison, 1996; Cohen et al., 1998; Cohen et al., 2002; Sytsma et al., 2004). These introductions impact ecological systems and processes, as well as altering the numerical species richness (e.g. Feyrer et al., 2003; Richman & Lovvern, 2004). An underlying mechanism for this trend has probably been the growth of shipping between Japan, and subsequently Korea, China and other East Asian countries, which has been an important feature of U. S. trade since World War II (Barsness, 1997). The rate of discovery for new invasions along the US Pacific Coast exhibits an exponential growth curve (Ruiz et al., 2000; see also Cohen and Carlton 1998 for San Francisco Bay), causing significant concern about impacts on wildlife resources and ecosystem function.

Ship arrivals affect the supply of potential colonizers, or propagules, that arrive to different port locations. There exists considerable variability in propagule pressure among ports in terms of the density, diversity, magnitude, frequency and duration of propagule supply that result from ships (Minton et al., 2005; Verling et al., 2005). Vessel behavior, such as ballast discharge, voyage routes, voyage durations, docking durations and hull maintenance, influence these characteristics of propagule pressure. In addition, some aspects of vessel behavior (e.g., speed, residence time) are associated with vessel type. Thus, understanding traffic patterns (maritime shipping models) is a key component for interpreting and predicting invasion outcomes.

Rodrigue et al. (2006) described three models of maritime transport that have implications for propagule supply:

1) Port-to-port: this is characterized by ships traveling regularly between two ports but with cargo transfers generally being unidirectional.
2) Pendulum: this involves a transoceanic voyage by a vessel, followed by a series of shorter coastwise port stops and then a return transoceanic voyage, more coastwise port visits and then the process repeated. Thus, two coastlines on opposite sides of one ocean are serviced.
3) Round the world: this model includes vessels that travel to a small number of ports on different continents such that a global circumnavigation may be achieved.

These three options refer generally to a vessel employed on a regular service route, but some vessels do not have a regular route, traveling to numerous destinations in a seemingly random fashion and representing a fourth option. These vessels are often referred to as 'tramp' ships and can often have a recent history of geographically dispersed port visits (see Minchin & Gollasch, 2003).

Each of these traffic patterns has relevance to propagule supply for the US Pacific Coast and elsewhere. For instance, the port-to-port model provides the potential for a high frequency of propagule transfers between both ports. Cargo directionality and source port(s) affect ballast water discharge patterns and opportunity for transfers with both ballast water and hull fouling. The pendulum model has the potential to act as a secondary disperser of NIS to ports that do not have direct links to the donor port. The connectivity between ports on the coastwise legs of the overall route means that ports without direct links to the transoceanic donor are still "downstream" and remain susceptible to transoceanic NIS, with the possibility of either (a) direct introduction from an overseas ship or (b) secondary spread from a domestic source population that was previously established. For the third and fourth maritime traffic scenarios, the receiving ports benefit in reduced frequency of propagule supply (fewer return arrivals by the same ships) but the scale of donor regions, and possibility of novel donor ports and novel NIS incursions, is increased.

Aims

Our aim was to document traffic patterns and associated WSA of commercial vessels operating in the states of California, Oregon and Washington. This was intended to characterize the magnitude of WSA flux and behavior of vessels operating along the West Coast, as a step toward considering potential implications for transfer of biota and invasions associated with ships' hulls.

The hull fouling vector differs from the ballast water vector in numerous important ways (Hewitt et al., in press), which are important when interpreting shipping traffic data and its link to marine introductions. The most obvious and important difference is that the latter is internal while the former is external. This has implications for propagule supply and variability – ships that do not discharge ballast do not deliver ballast borne propagules whereas external hull fouling has the potential to deliver propagules on each arrival to port. Our analysis considered potential consequences of observed traffic patterns for propagule supply by the hull fouling sub-vector, including comparison with ballast water delivery, but a formal analysis awaits quantitative biological data on biofouling that is not yet available.

Methods

We analyzed vessel arrivals data over a two-year period between July 2003 and June 2005. The state programs in California, Oregon and Washington that monitor ballast water reporting provided data on vessel arrivals. Using these data, our objective was to characterize West Coast commercial maritime traffic by examining variation among ports, ship types, donor regions, and wetted surface area (WSA). For our purposes, domestic coastal arrivals, or internal traffic, were those ships whose last port-of-call was in California, Oregon or Washington, whereas all other arrivals were considered overseas since they originated from outside of the three western states.

When examining the magnitude of the hull fouling vector, we used a measure of the underwater surface area of ships, or wetted surface area (WSA). WSA is a measure of the space available to marine organisms (fouling species) on the surfaces of ships that can be transferred from port to port. It is analogous to ballast water volumes for the BW vector. WSA for each vessel was calculated as follows (from Van Maanen & Van Oossanen, 1988):

$$WSA= L\,(2T + B)\,C_M 0.5\,(0.4530 + 0.4425\,C_B - 0.2862 C_M – 0.003467 B/T + 0.3696\,C_{WP}) + 2.38 A_{BT} / C_B$$

Where: L = length, T = draft, B = breadth, C_M = midship coefficient, C_B = blocking coefficient, C_{WP} = waterplane coefficient, A_{BT} = cross-sectional area of bulbous bow (calculated as a percentage of the immersed area of midship). The coefficients and bulb area percentages for different vessel types are published in Lewis (1988). Although length should technically be the waterline length of the hull, such data are not available for the commercial fleet so ship length is used.

We carried out ordinations using non-metric multidimensional scaling (MDS) in PRIMER (Clarke and Warwick, 2001). Among other applications, MDS is usually carried out in community ecology to assess community organization and in population ecology to analyze morphometric differences and similarities among populations. For community analysis, the plot produced helps to determine the similarity/dissimilarity of habitats or sites by grouping those that share species close together and separating habitats or sites that do not share species. In our use of MDS here, we considered ports as sites and ships as 'species' such that the plots produced could help us determine the similarity between ports based on the frequency with which different ships arrived: ports plotted close together would have the same subset of ships arriving frequently while ports plotted apart did not often receive the same ships. In addition, a stress value is produced to reflect how well the plots condense the multivariate information into two dimensions (the closer to zero the better the 2-d representation of the data).

We assessed the arrivals and WSA data with the following questions in mind:

- How much WSA arrives to the West Coast and how does it vary by state, port, donor region and ship type?
- What is the frequency distribution of individual vessel arrivals and how does it vary by port and ship type?
- How connected are West Coast ports to global ports and to each other?
- Can we discern trends in voyage routes and how much variability exists within and among ship types? Do these trends match the aforementioned models of maritime transport geography?

Results

West Coast: arrivals, donor regions and wetted surface area

Over a two-year period between July 2003 and June 2005 inclusive, 29,282 vessel arrivals to West Coast ports were recorded. When compared with data from the Maritime Administration and analysis of reporting compliance from the three West Coast states, this figure reflects greater than 95% of the actual number of vessel arrivals (Maritime Administration, 2006; Falkner et al., 2005; Simkanin & Sytsma, 2006). The only significant under-reporting may have occurred for barges because of regulation changes regarding reporting for this vessel type. The totals for California, Oregon (including all Columbia River ports) and Washington (excluding Columbia River ports) were 19512, 3983 and 5787, respectively.

Traffic emanating from outside of the three western states amounted to 64% of the overall total. Coastal arrivals accounted for 34% of all vessel arrivals to West Coast ports (2% of arrivals were from an unknown origin). The ratio of overseas to coastal arrivals (close to 2:1) was consistent across the three states (Friedman's test, $p > 0.05$ [fig. 1]). Transoceanic and eastern Pacific intra-oceanic arrivals dominated overseas traffic with 14,955 vessels arriving from a combination of Japan, China and Korea in the NW Pacific and Alaska, British Columbia and Mexico in the NE Pacific (fig. 2). The worldwide distribution of previous ports-of-call also included the South Pacific, North and South Atlantic, and Indian Oceans as well as semi-enclosed seas including the Gulf of Mexico, Caribbean, Mediterranean and Baltic. Interoceanic arrivals accounted for just 6.1% of the total overseas influx.

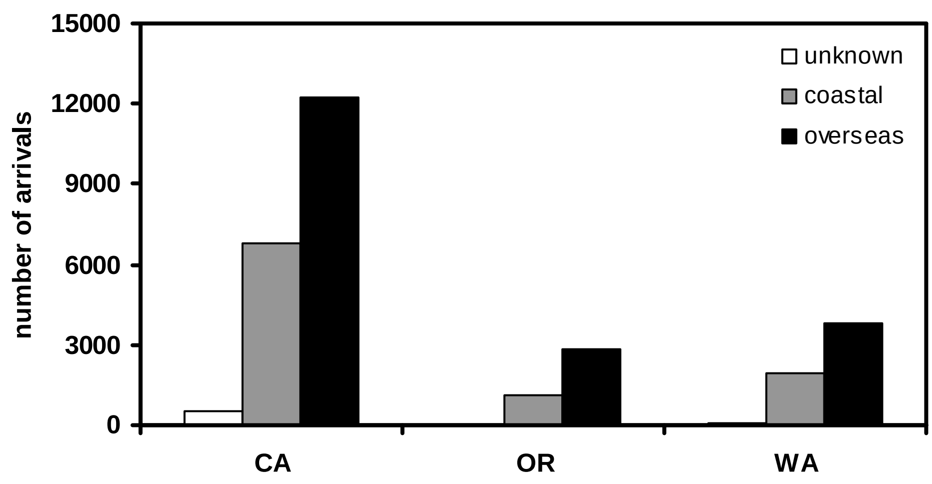

Figure 1. Arrivals to each West Coast State from overseas and domestic coastal ports. The ratio of overseas to coastal arrivals did not differ significantly between states (approximately 2:1).

The WSA for all arrivals amounted to 265.6 million m^2 – equal to 102 square miles. The majority of this WSA arrived with containerships, which accounted for just less than half of the total (126.5 million m^2). Tankers ranked second in terms of WSA donation with 57.2 million m^2. These two vessel types are the only ones from the eight categories whose proportional share of total WSA is higher than their share of total vessel arrivals (Fig. 3).

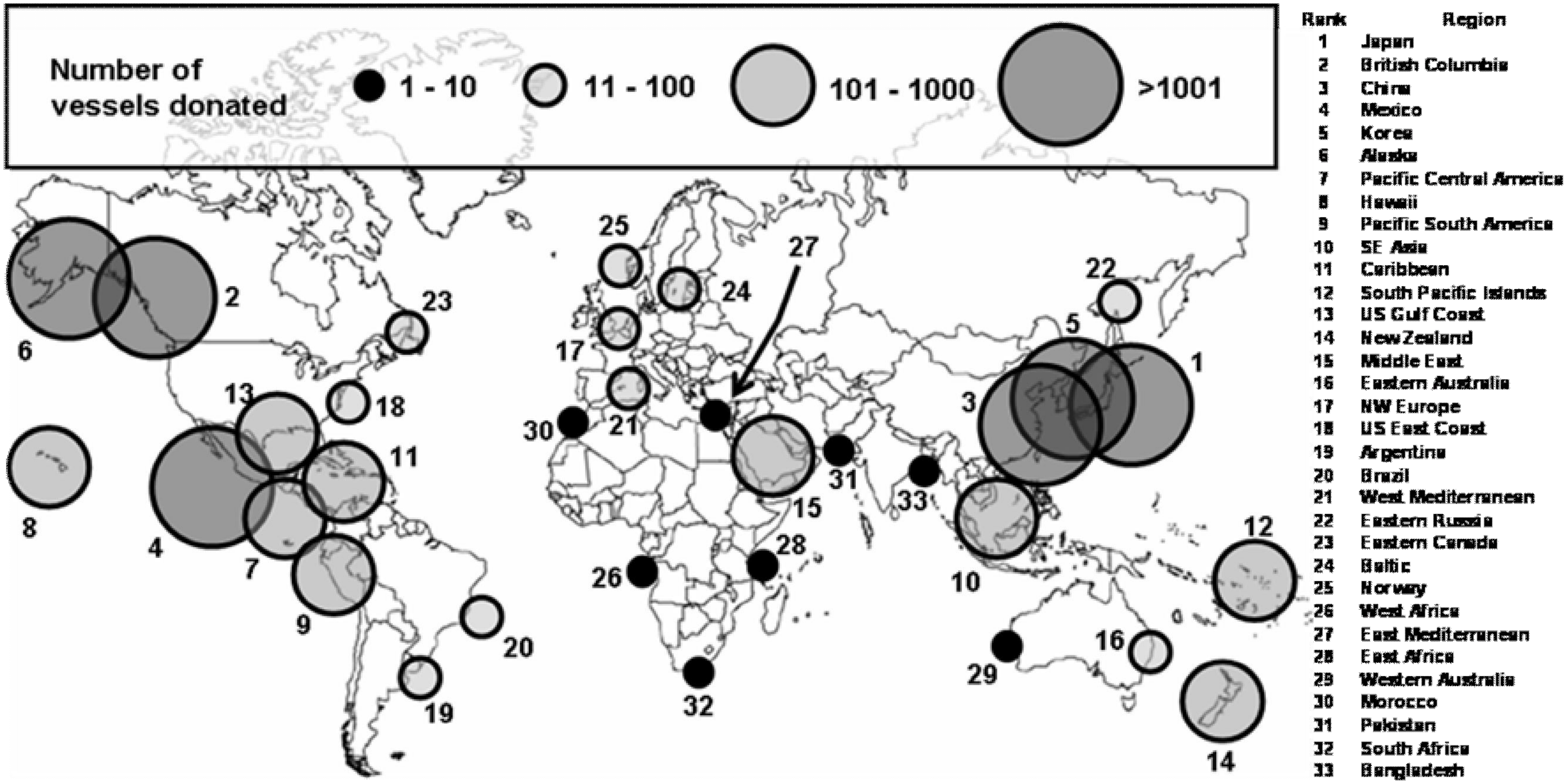

Figure 2. Donor regions for overseas arrivals to the US West Coast. Donor ports were assigned to 33 regions (listed) throughout the world and the size of the circles represent volume of vessel arrivals. Data are from the previous ports listed on ballast water reporting forms of vessels arriving to California, Oregon and Washington (between July 2003 – June 2005).

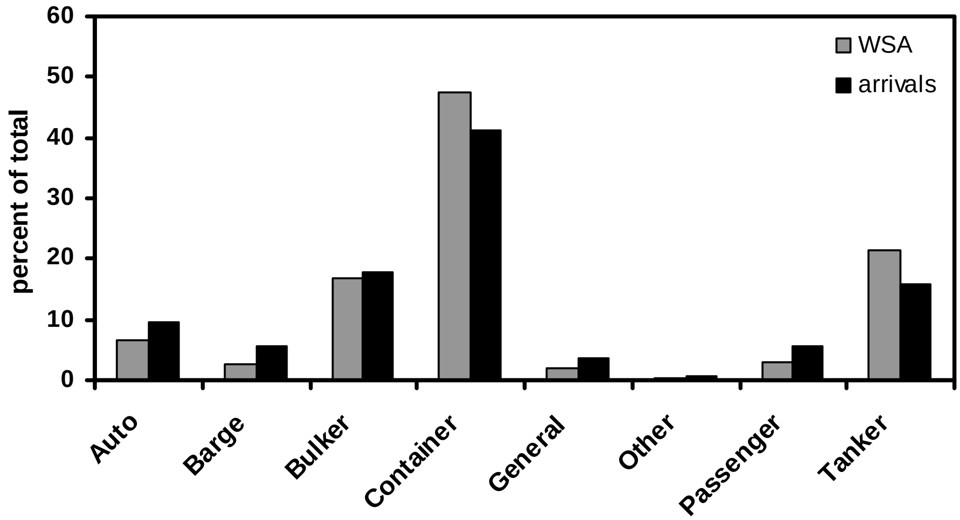

Figure 3. The percentage of total arrivals and WSA by vessel type. The percent contribution to total arrivals and WSA by each vessel category is shown. Note that containerships and tankers are the only vessel types to have a higher WSA percentage than arrivals percentage.

Variation by vessel type

U.S. West Coast maritime shipping is dominated by containership traffic. Primarily because of the number of arrivals, but also due to their large size, containerships accounted for a greater than 40% share of WSA totals for the entire coast. Tankers, containerships, bulkers and auto carriers were the vessel categories that had the largest underwater surface area, each with an average of greater than 6000 m^2 (fig. 4). On average, it would take roughly two auto carriers to deliver the same amount of underwater surface area to a port that one tanker would deliver. All vessel types had significantly different mean WSA (ANOVA, d.f. = 7, F = 2938.07, $p<0.001$) with the exception of passenger and general cargo vessels. In terms of arrivals, the only vessel type to have significantly more domestic coastal arrivals than overseas arrivals was barges, whose movements reflected a smaller scale and more regional transport geography. Containerships arrived twice as frequently from overseas ports as coastwise domestic ports and there were 4.5 times as many overseas bulker arrivals than domestic bulker arrivals.

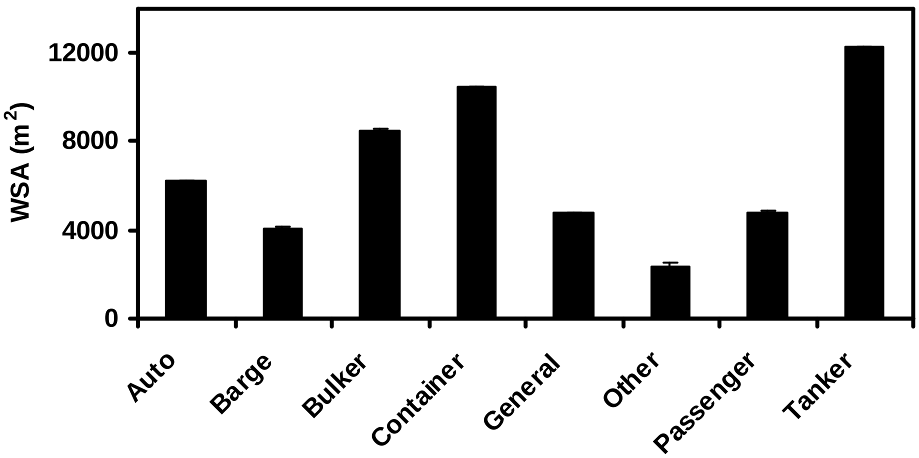

Figure 4. The mean Wetted Surface Area of each ship type. The mean (+/- 1 SE) WSA for each vessel type is shown. With the exception of passenger and general cargo vessels, each pair-wise comparison of ship types was significantly different.

The frequency of arrivals by vessels showed two distinct patterns; each pattern displayed by four ship types each (fig. 5, which used California data only). The first pattern, characterized by bulkers, shows a high proportion of vessels that were one-time arrivals and few ships arrived on multiple occasions, creating an L-shaped curve. Tankers, general cargo and unknown/other vessel types also displayed this pattern of arrival frequency (fig. 5 [plots in the left column]). For each of these vessel types, more than 75% of vessels arrived five times or fewer and at least 35% of vessels arrived just once over the two years analyzed. In contrast, for the other pattern of arrival frequency, characterized by containerships, less than 20% of vessels were one-time arrivals. This trend, also displayed by barges and passenger vessels, does not have the distinct skew to the left of the plot (L-shape) and 50% or more of these vessels arrived on more than five occasions fig. 5 [plots in the right column]). One passenger vessel reported 317 arrivals over the two year period to various ports in California. Auto carriers also displayed an arrival frequency pattern similar to containerships with less than 20% of vessels arriving once but with greater than 60% arriving on five occasions or fewer.

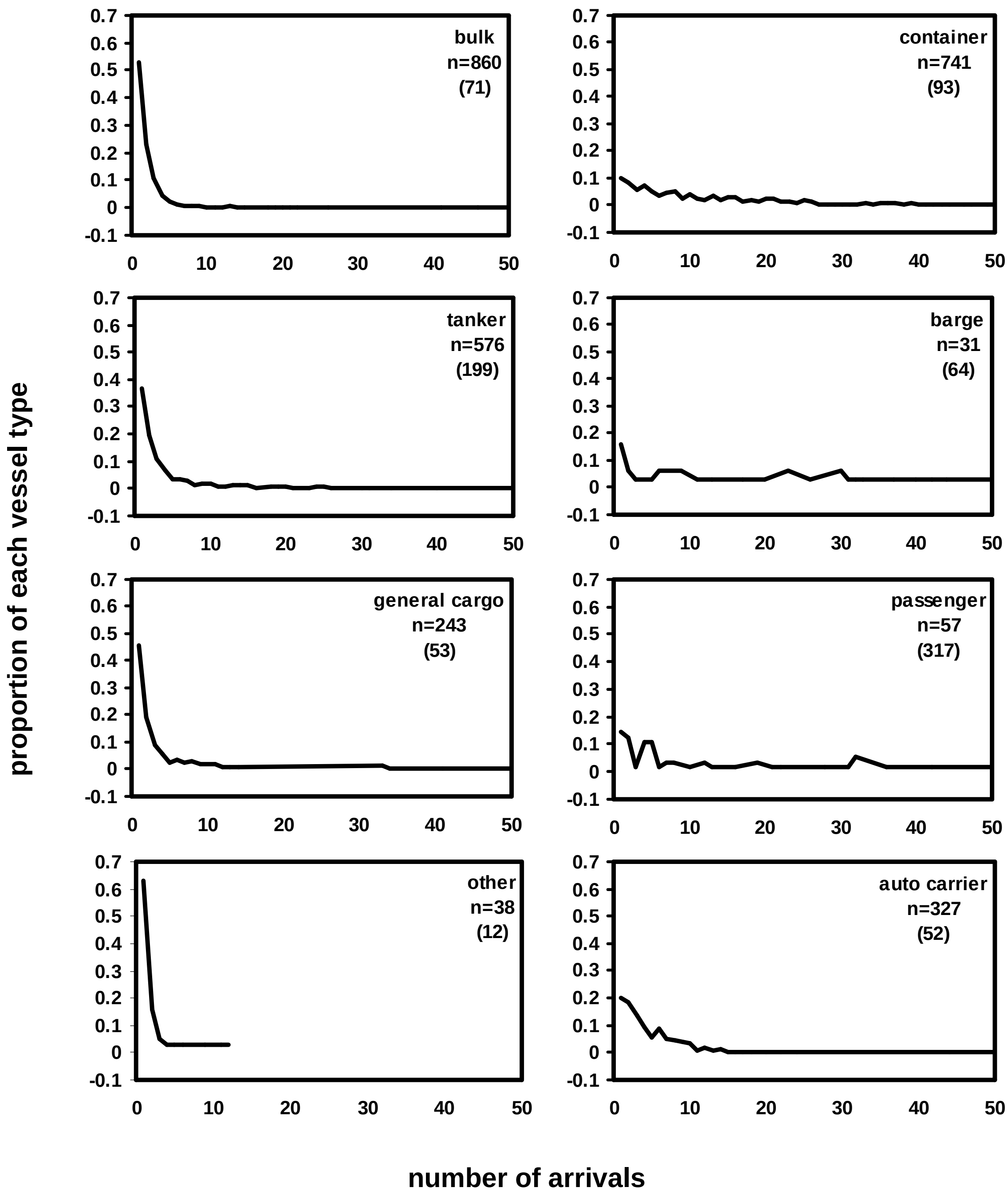

Figure 5. The frequency of arrival for each vessel type to California ports. The number of arrivals over two years for each vessel is plotted as a proportion of each ship type. For each plot, the scales are equal such that the x-axis is scaled to 50 arrivals over two years. The maximum number of arrivals for each ship type is in parentheses (this number represents the maximum extent of the x-axis). The number of ships (n) per vessel type is also provided. Note that the four left-hand plots show a distinctive L-shaped curve whereas the four to the right do not have a high proportion of one-time arrivals.

Variation by port

The effect of port on vessel traffic is an important feature of Pacific Coast maritime shipping. Bulkers were the dominant ship type arriving at 13 different ports, most notably the riverine ports in the Columbia River, Sacramento and Stockton (Table 1). The Port of Portland was the only port of the top five (ports receiving greater than 1000 arrivals per year) that did not have containerships as the dominant vessel type. For the other four, LA/Long Beach, Oakland, Seattle and Tacoma, containerships had a greater than 50% share of arrivals. Tankers also had a dominant contribution to several ports, contributing greater than 60% of vessels to seven different ports from Ferndale in northern Washington to El Segundo in southern California. The ports of Hueneme, Anacortes, and Everett, were dominated by auto carriers, barges and general cargo vessels respectively, whereas passenger vessels dominated in San Diego and Avalon with 35% and 98% of arrivals, respectively.

There were also important differences and similarities among West Coast ports in terms of their links with other worldwide ports and with each other. LA/Long Beach is the major port system along the West Coast and accounted for fully 37% of all arrivals to the three western states. This volume of traffic arrived from 345 different ports throughout the world and departures from LA/Long Beach were destined for 305 ports (fig. 6). Eight other ports received ships from greater than 100 ports, four of which were Columbia River ports. In general, ports located within the major shipping centers of Puget Sound, the Lower Columbia River, San Francisco and LA/Long Beach had high numbers of port linkages for incoming and outgoing traffic. The smaller ports (generally on the outer coasts of all three states) tended to have fewer (<50) connections with other ports throughout the world.

For domestic coastwise traffic, a similar picture emerged regarding the inter-connectedness of West Coast ports (fig. 7). Ports in the major port systems were connected to over 15 ports with LA/Long Beach receiving and donating vessel traffic to over 30 other coastal ports. Smaller ports were generally connected to fewer than ten coastwise ports.

Table 1. Arrivals to West Coast ports from July 2003 to June 2005. The percentage of arrivals from each ship type arriving to major West Coast ports is plotted. Ports are arranged from north to south and percentages in bold show the dominant vessel types arriving to each port.

arrival port	auto carrier (%)	barge (%)	bulker (%)	container (%)	general cargo (%)	other (%)	passenger (%)	tanker (%)	total arrivals
Ferndale	0.0	11.6	6.3	0.0	0.0	0.0	0.0	**82.1**	207
Anacortes	0.0	**46.7**	9.3	0.0	1.3	0.4	0.0	42.3	227
Port Angeles	0.7	4.4	12.1	0.4	7.7	1.8	0.7	**72.2**	273
March Point	0.0	19.8	1.8	0.6	0.0	0.0	0.0	**77.8**	167
Cherry Point	0.0	36.4	0.3	0.0	0.0	0.0	0.0	**63.3**	354
Everett	18.2	0.0	36.4	0.0	**39.4**	3.0	0.0	3.0	33
Seattle	0.9	0.5	17.7	**65.5**	1.8	1.6	11.6	0.5	2211
Tacoma	26.5	0.5	14.4	**52.6**	1.8	0.8	0.0	3.4	2113
Olympia	29.4	0.0	**64.7**	0.0	5.9	0.0	0.0	0.0	51
Aberdeen	12.7	0.0	**68.4**	1.3	13.9	3.8	0.0	0.0	79
Other WA ports	5.6	6.9	13.9	1.4	15.3	8.3	1.4	**47.2**	72
Astoria	0.7	4.2	**74.3**	0.0	0.0	8.3	11.1	1.4	144
Kalama	0.0	0.0	**95.3**	0.4	0.0	0.0	0.0	4.3	276
Longview	0.0	0.3	**96.1**	0.0	0.0	0.0	0.0	3.6	387
Vancouver	10.1	8.8	**69.0**	2.0	0.0	0.5	0.2	9.5	613
Portland	19.1	24.5	**34.2**	14.7	0.0	1.0	0.2	6.3	2436
Coos Bay	0.0	0.0	**100.0**	0.0	0.0	0.0	0.0	0.0	97
Other OR ports	20.0	0.0	**70.0**	3.3	0.0	0.0	0.0	6.7	30
Humboldt	0.0	8.3	**68.3**	1.7	13.3	3.3	5.0	0.0	60
Redwood	0.0	0.0	**97.9**	0.0	0.0	2.1	0.0	0.0	97
Sacramento	0.0	5.7	**69.8**	0.0	14.2	0.0	0.0	10.4	106
Carquinez	15.3	9.5	18.1	0.2	0.7	0.4	0.0	**55.8**	824
Richmond	10.7	9.5	9.5	1.0	0.4	0.4	0.0	**68.5**	828
San Francisco	1.0	4.5	18.6	5.9	3.9	0.9	18.6	**46.7**	814
Oakland	2.5	0.0	4.1	**93.0**	0.4	0.0	0.0	0.0	3421
Stockton	1.5	0.8	**57.3**	0.4	6.9	0.0	0.0	33.2	262
Avalon/Catalina	0.0	0.0	0.0	0.0	0.0	0.0	**98.5**	1.5	67
El Segundo	0.0	5.6	0.0	0.0	0.3	0.0	0.0	**94.1**	354
Hueneme	**57.6**	0.0	0.3	0.3	38.0	0.3	0.3	3.3	693
LA/Long Beach	5.9	3.3	11.4	**54.1**	4.2	0.3	6.8	14.0	10858
San Diego	28.6	3.1	11.2	3.6	13.4	3.9	**35.0**	1.1	993
Other CA ports	2.2	0.0	0.7	1.5	0.0	1.5	17.8	**76.3**	135

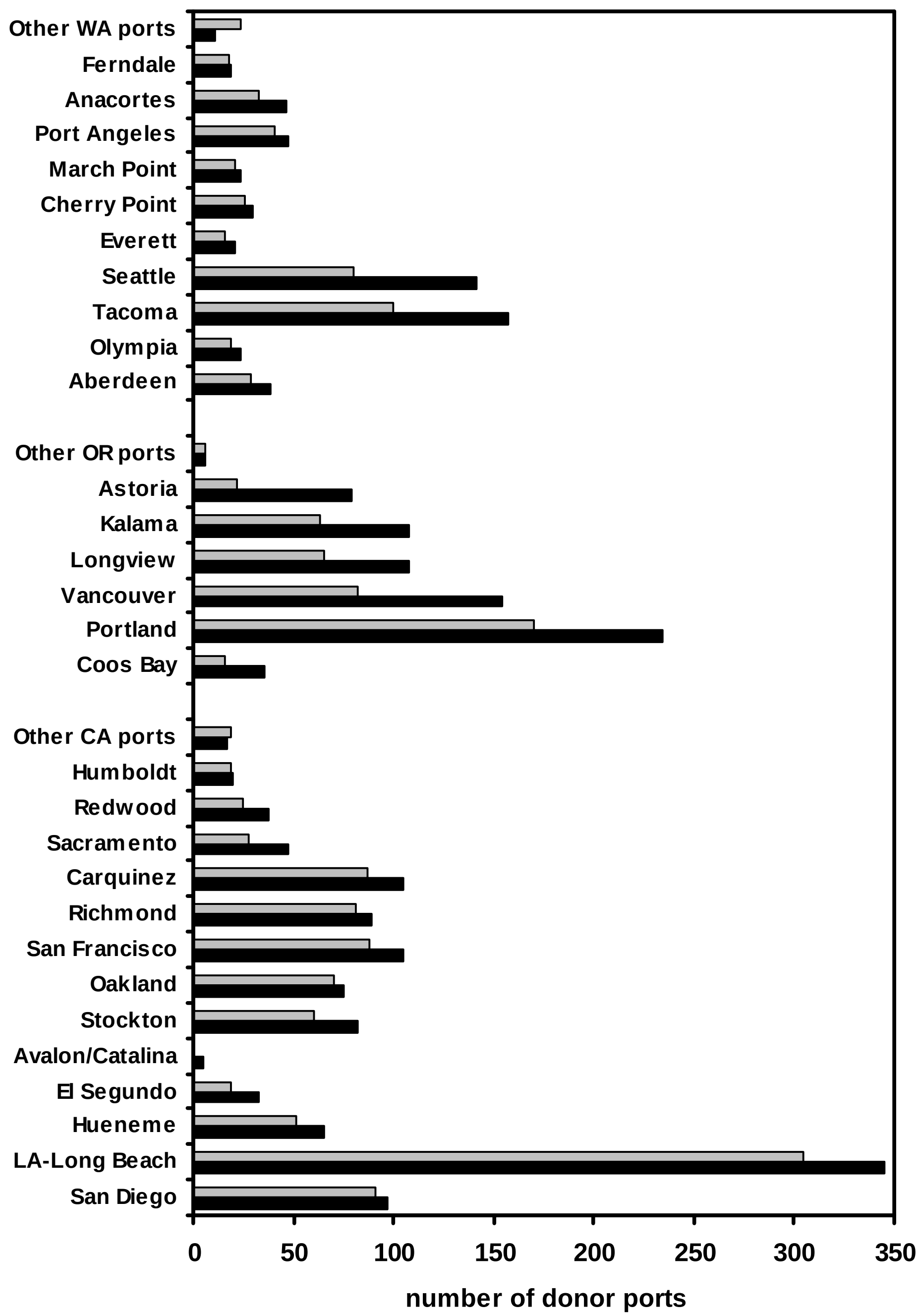

Figure 6. The number of worldwide donor and recipient ports connected to West Coast ports. For 36 West Coast ports (arranged from south to north), the numbers of donor ports are plotted using last-port-of-call data (black bars) and the number of recipient ports using next-port-of-call data (grey bars) from each vessels' ballast water reporting form.

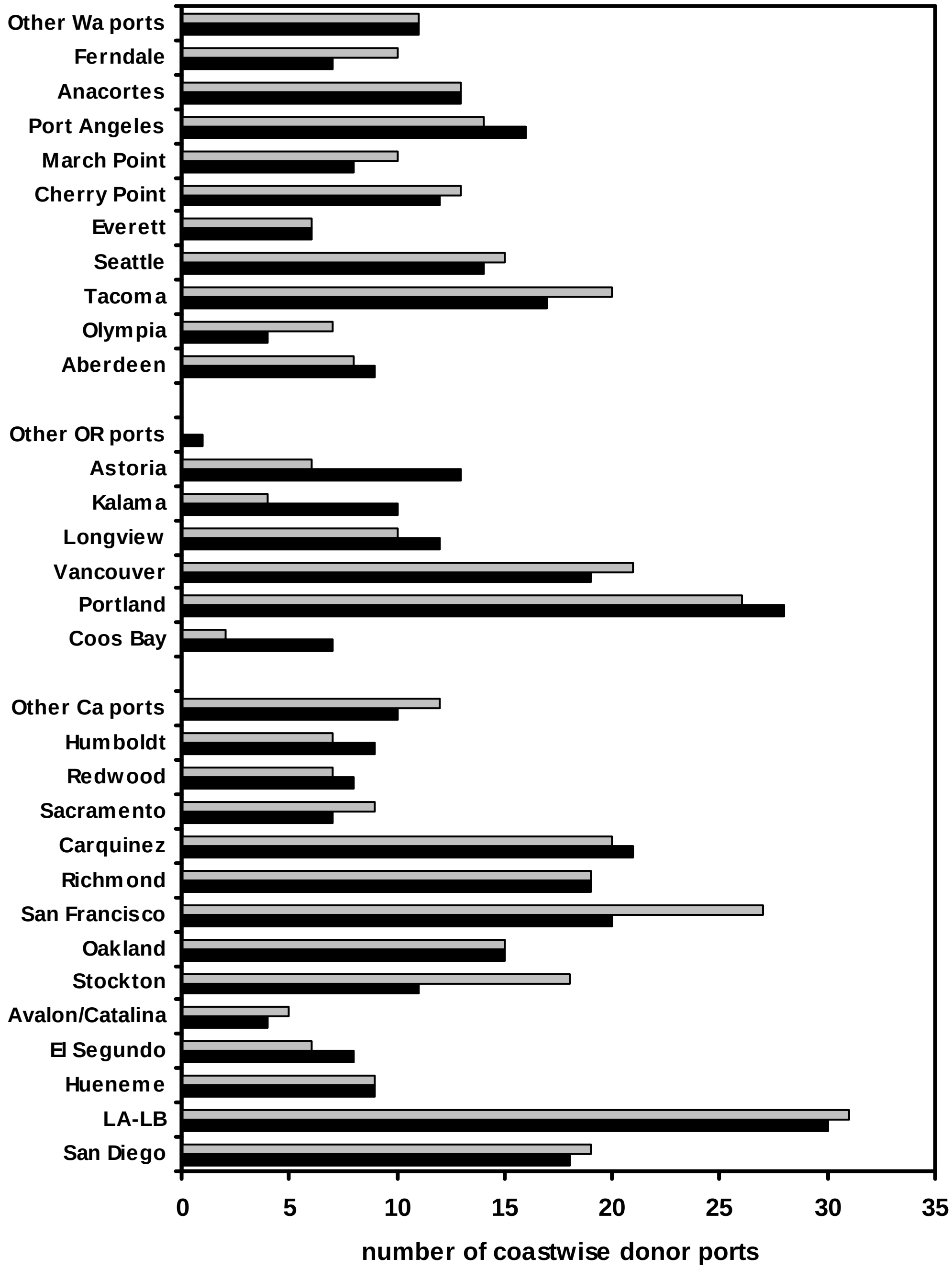

Figure 7. Connectivity between West Coast ports. The number of donor ports from which vessels arrive (black bars) and recipient ports to which vessels are donated (grey bars) from domestic coastwise arrivals and departures is plotted with ports arranged from south to north.

Arrivals and port connectivity

For two major ship types – bulkers and containerships – we examined further how vessel traffic influenced port connectivity using multivariate techniques. Using bulker arrival data (fig. 8 [A and B]), three observations could be made from the plots:

1) There were many ports that received numerous bulkers but no distinctive clusters of ports were observed.
2) Despite the lack of distinct clustering, ports within California and the Columbia River tended to group together whereas Washington ports were more dispersed.
3) LA/Long Beach and the riverine ports of Vancouver, Stockton, and Portland formed the core ports to which bulkers arrived, and these ports received the largest abundances of this ship type (fig. 8B).

In contrast, there were few ports that received numerous arrivals of containerships (fig. 9A, see also table 1). This vessel type formed distinct hierarchical clusters whereby the core ports of LA/Long Beach and Oakland both received very many of the same vessels and were positioned adjacent to each other in the plot with Seattle which received fewer vessels but a subset of the same ships nonetheless. The Ports of Tacoma and Portland were secondary to these core ports, and had fewer arrivals but many were the same ships that frequented the core ports (hence their proximity in the plot). The tertiary ports of San Diego and San Francisco received fewer still and were positioned equidistant from the core and secondary ports. Furthermore, the source of containerships varied between ports (fig. 9B). The two major ports had contrasting proportions of overseas and domestic traffic – LA/Long Beach receiving ships primarily from overseas and Oakland receiving containerships mainly after shorter coastwise voyages. In fact, 64% of all containership traffic to Oakland arrived from LA/Long Beach, hence their proximity in the MDS plot (fig. 9A).

The multivariate plots (figs. 8 and 9A) combine data on the number of arrivals and the identity of individual ships that help determine the patterns of vessel traffic and port linkages. The arrival frequency trends of both ship types is reflected in the plots; bulkers have a high proportion of one-time arrivals and show less distinct clustering than

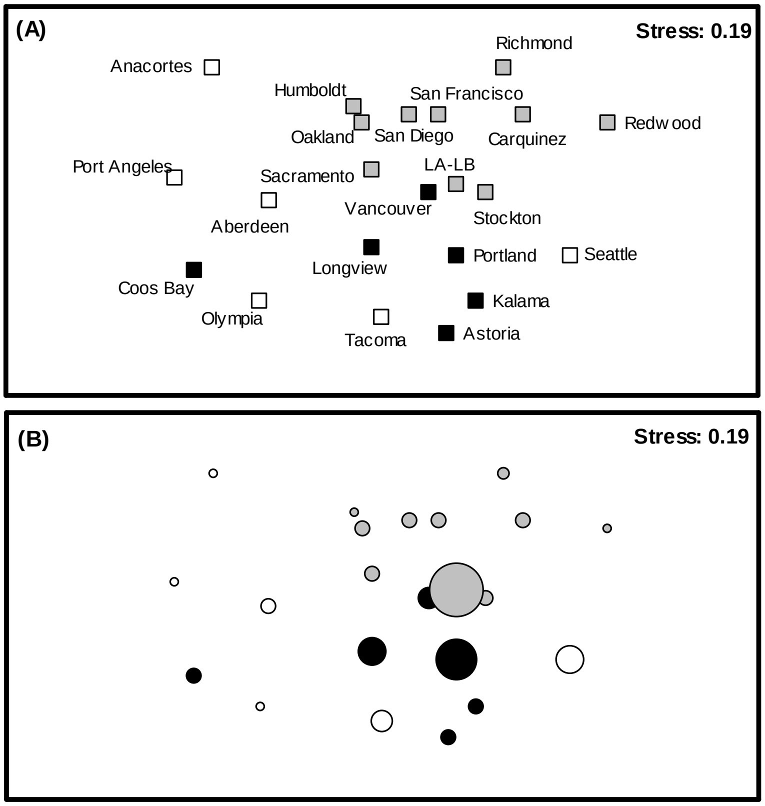

Figure 8. Connectivity of ports using bulker arrivals. In each plot, ports close together have had many of the same vessel calls, whereas those far apart have not shared many vessels. Bulkers were used in both plots (A) and (B). Plot (B) uses the same data as plot (A) but labels are removed and symbols changed to bubble sizes that reflect the numbers of bulker arrivals to each port. Grey, black and white symbols reflect California, Oregon (& Columbia River), and Washington (excluding Columbia River), respectively.

containerships, which have few one-time arrivals (fig. 9A, note also that the stress values reflect a better organization of ports by containerships than by bulkers). The port linkages also differ for both ships types; for containerships the connectivity between ports results from direct coastwise movements of ships, exemplified by the traffic moving from LA/Long Beach to Oakland. In contrast, bulkers tend not to arrive repeatedly and tend to arrive from overseas such that even though the same ships arrive to different ports, they don't often arrive directly from another coastal port (even though some direct voyages do occur). These contrasting plots reveal further differences in voyage routes and behavior between the dominant vessel types trafficking to Pacific Coast ports.

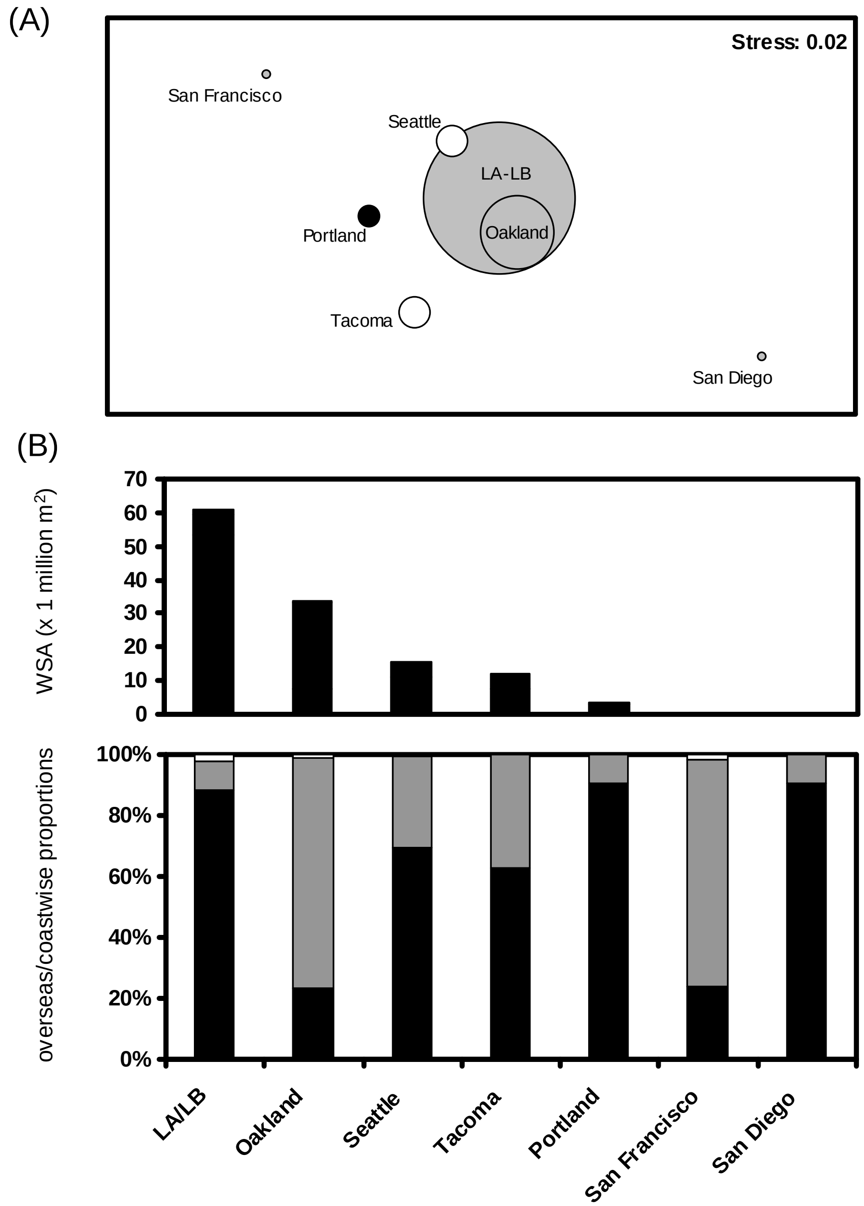

Figure 9. Port connectivity and origin of Containership arrivals. Plot (A) is an MDS showing the similarity of ports based on containership arrivals data and the size of the bubbles reflects the numbers of arrivals. Ports plotted close to each other share many arrivals of the same ship whereas those far apart do not. Grey, black and white circles reflect California, Oregon (& Columbia River), and Washington (excluding Columbia River) ports, respectively. Plot (B) shows the containership WSA contribution to each of the seven ports (top panel) and the proportions that arrived from overseas and domestic coastwise origins (bottom panel). Black, grey and white bars represent overseas, coastwise and unknown sources, respectively.

Comparison with ballast water estimates

An analysis of the actual ballast water discharge data for the arrivals in our database is underway but in the interim we used published data to provide a coarse estimate of the number of ships discharging and magnitude of ballast water discharged for our West Coast dataset. The data comes from a recent three-year national-scale analysis of variability in ballast water management among ship types (Verling et al., 2005) and we applied it to our data set with the assumption that it was reflective of West Coast BW management trends and in the knowledge that these are crude estimates. Using these data, we estimated that roughly 39.5 million metric tons (MT) would have been discharged across California, Oregon and Washington over the course of our analysis period (2 years, [table 2]).

Table 2. Ballast water (BW) discharge patterns and West Coast shipping. Data from Verling et al. (2005) are tabulated and used to estimate the numbers and volumes discharged by each ship type for our West Coast data set.

	A	B	C	D	E
	number of vessels	estimated % discharging BW (from Verling et al., 2005)	estimated mean volume discharged (MT) (from Verling et al., 2005)	number discharging (A x B)	volume discharged (MT) (C x D)
auto	2788	17.6	1100	490.7	539756.8
barge	1606	n/a	n/a	n/a	n/a
bulk	5220	40.2	12500	2098.4	26230500.0
container	12093	17.2	1900	2080.0	3951992.4
general	1091	18.8	3800	205.1	779410.4
other	196	8.6	5800	16.9	97764.8
passenger	1618	55.1	900	891.5	802366.2
tanker	4670	16.4	9200	765.9	7046096.0
Total	29282				39447886.6

The variability in proportions of vessels discharging, and quantities of ballast discharged, highlighted the impact of vessel type on BW supply. The number of containerships that discharged BW was approximately equal to bulkers, despite bulker arrivals amounting to less than half that of containerships. Bulkers contributed 66% of all BW discharge on the West Coast whereas containerships supplied just 10% (assuming that each discharging vessel discharged the mean value for that vessel type). This contrasts with the WSA magnitude delivered by these two vessel types that favored containerships over bulkers by a factor of 2.8. Passenger vessels, despite a high proportion of discharging vessels, had low volume discharge events and thus contributed a mere 2% of all BW discharged. When comparing mean WSA between tankers and auto carriers, the magnitude favored tankers by 2:1 but for mean BW discharge the ratio is greater than 8:1.

Discussion

The hull fouling vector of NIS has been inadvertently subjected to management methods for centuries because of the hindrance that fouling, non-native or otherwise, brings to ships (Carlton, 1985). Nonetheless the vector has been a potent agent of species transfers leading to many successful inoculations; estimates for all U. S. coastal introductions (316 species) made possible by hull fouling transfers range from 19% to 37% (Fofonoff et al., 2003). It has been suggested that in the southern hemisphere the proportion of introductions attributed to hull fouling may be even higher (Hewitt et al., 2004). These species transfers on the external surfaces of ships have continued throughout periods where sweeping changes have occurred in how the vector works – the change from wooden to steel hulls being one of the most drastic. Examining trends of previous, current and future transfers and introductions by this vector requires that such variability be taken into account. For today’s commercial fleet, such assessments reveal interesting patterns of variability among ship types and spatial scales that may lead to a better understanding of this vector’s effectiveness. They may also lead to better predictions of where, when and what species could be transferred in the future such that large-scale homogenization of biotas does not become a side effect of commercial globalization.

On the West Coast of North America, examples of the threat of biodiversity loss and biotic homogenization can be found coast-wide and in individual bays and estuaries. In particular, significant numbers of NW Pacific species have become numerically dominant at local and regional scales (Cohen et al., 1998; Cohen et al., 2000; Ruiz et al., 2000). Many of these species have made their way to the West Coast on transoceanic voyages, and as the number of new arrivals continues to grow and shipping voyages become more varied and frequent, detailed analyses of variability in propagule supply by shipping vectors will be important.

West Coast shipping traffic and wetted surface area

The underwater surface area arriving to the West Coast on ships is quite considerable. Approximately 15000 vessels arrive per year, donating an estimated 138.8 million m^2 (larger than the land area of San Francisco County) of WSA annually. Of course, not all of this area is covered in fouling organisms. Detailed studies of organism density and diversity associated with ships' hulls of the northern Pacific, or with sufficiently large numbers of replicate hull surveys to characterize associated biota for any global region, are presently lacking. It is well known that commercial vessels continue to transfer species on their hulls (Gollasch, 2002; Coutts & Taylor 2004; Godwin 2005a; Davidson et al., 2006a), but the variability in density of hull-mediated organism transfers is not well understood; this study is the first to attempt to improve our understanding of variation in magnitude and spatial pattern of WSA flux on the West Coast. Interpreting the associated biotic flux requires significant further sampling efforts, as these have only just begun. For two recent studies in this region, estimates of fouling on individual ships ranged from <1% to 95% (Ruiz et al., 2004; Davidson et al., 2006a). Until a greater number of surveys are conducted, this paucity of data will continue to hinder any attempt at accurate estimates of the strength of the contemporary hull fouling vector.

The geographic scale of vessel arrivals to Pacific Coast ports is global, but source ports throughout the North Pacific Ocean predominate with at least 90% of arrivals emanating from NE Asia, Hawaii, and the West Coast of Central and North America (domestic and foreign coastwise traffic). Although a nonindigenous species could come from any of the donor ports throughout the world, especially from high-density inocula, it is more likely that species with a high potential for repeated inoculation will become established. The influence of high frequency of inoculation to the outcome of introductions has been shown theoretically (Drake & Lodge, 2006), as has the influence of density-dependence on invasion establishment (Grevstad, 1999). For the hull fouling vector, organism density data is required if these interacting factors (density and frequency) are to be investigated further.

Although interoceanic and transoceanic voyages are a source of many NIS, an added issue in examining regional scale vector and NIS patterns is coastwise traffic. Such coastwise traffic (ranging from Central America to Alaska) may act as a mechanism for hull-mediated primary NIS transfers but also pose the additional risk of increasing the range of an already established transoceanic NIS (secondary spread). This may be a high risk vector to West Coast bays and harbors, especially those with strong links to San Francisco Bay, given its high NIS load. In fact, some high-profile NIS are restricted to the Bay area (e.g. the Asian clam *Corbula amurensis*) and the opportunity for this species to spread further in its non-native range might only be afforded by hitch-hiking on ships (though more likely in ballast water) where it has been found in fouling communities, albeit on ships that have been stationary for some time (Davidson et al., 2006b). As congestion on road and rail shipping networks grows as an issue of concern on all three coastlines of the U. S., an increase in domestic 'short sea' shipping is likely (Maritime Administration, 2004). It will be interesting to assess the implications of this trade and traffic on the hull fouling (and ballast water) vector and on species distributions over regional scales.

The effect of ship type and port on hull fouling

The value of vessel type in assessing the variation that exists in vector metrics for hull fouling is significant. Ship types are tightly coupled to the organization of maritime trade and have particular biological relevance to an external vector of species transfers; the variability in vessel speed, port durations and voyage routes between ship types is usually greater between ship types than within ship types (Davidson et al., in prep). Different cargoes and ship types require a variety of port capabilities, ranging from general (and labor intensive) loading and unloading of bulk materials and autos, to specialized equipment required at oil, grain and container terminals. This influences port duration times and voyage routes – factors that probably play important roles in biofouling extent and composition on vessels.

Voyage routes and the origin of WSA showed distinct differences between ship types. Barge voyages were overwhelmingly coastwise (x 7.8), tankers were divided almost equally between coastwise and overseas, containerships were predominantly overseas (x 2.1) and bulker WSA arrived from overseas sources 4.6 times more frequently than from coastal sources. These patterns are further refined by the interaction between ship type, port and voyage origin. For example, containerships arrived to seven ports with LA/Long Beach and Oakland as the primary recipients of much of the container traffic. The flux of ships to these two ports accounts for much of the variability that occurs throughout the West Coast in terms of containership traffic. Although twice as many containerships arrive from overseas than from other domestic West Coast ports, this ratio varied widely from port to port, with Oakland in particular receiving more regional than international traffic (fig. 9), further highlighting the possibility of secondary spread.

We have also demonstrated how the magnitude of the hull fouling vector, measured as mean WSA, varies by ship type. The overall amounts and proportions of WSA donated by each ship type was a function of arrival frequency and mean WSA, and for the West Coast states, highlighted the dominance of containerships in terms of vector magnitude. The two largest ship types (in terms of mean WSA), containerships and tankers, were the only vessels whose proportional share of WSA was larger than their share of arrivals (fig. 3). Thus, these two largest vessel types have a larger than average contribution to WSA magnitude whereas the other six have a lower than average contribution. This study has also shown how frequency of arrival is linked closely with ship type. The effect of initial inoculant size is known to be significant in determining the success of population, but the frequency of inocula among other factors is also a determining factor (Grevstad, 1999; Drake & Lodge, 2006). Determining the biological significance of these factors, however, requires further hull sampling in order to couple the effects of ship type with biofouling accumulation. Without these measures of organism density, it is difficult to determine how density interacts with diversity, frequency, magnitude and duration of propagule delivery to affect invasion success.

Comparisons with ballast water

In the same way that ballast water largely consists of water with some organisms entrained in it, it appears likely that for the vast majority of ships most of the underwater area consists of painted surfaces with patches of biofouling. It may seem an obvious point but it is worth mentioning because of its relevance to measuring and predicting propagule pressure from ships. Previously, Drake and Lodge (2004) used vessel arrivals as a variable for estimating propagule pressure to predict the number of introductions to different ports. Other studies have used shipping tonnage as their measure of shipping activity (Ricciardi, 2001; Wonham & Carlton, 2005). Similarly, Niimi (2004) suggested that containerships play an important role in the invasion risk to ports worldwide because of their BW activity and arrival frequency. It is important to note, however, that propagule supply is decoupled from each of these measures. There is substantial variability in the magnitude of potential inocula (Verling et al., 2005; Davidson et al., in prep), but these measures of volume (for BW) and area (for hull fouling) are decoupled from propagule supply as well. They do, however, add to our understanding of the variation in potential propagule delivery that is unaccounted for by arrivals data alone, and when combined with density data, will provide measures of realized propagule delivery.

A ranking of vessel types, using BW estimates provided by Verling et al. (2005) and our data (table 2), showed that each comparison of BW measures and WSA measures per ship type did not match each other or the ranking for vessel arrivals (table 3). Ranks of WSA measures more closely resembled the ship arrival ranking than BW magnitudes. These differences in ranks across comparisons highlighted the variation in vector magnitude that exists among ship types and shows the contrast in scale of variation between vectors among ship types. Individual BW discharge events can range from volumes between zero and approximately 100,000 metric tons (Minton et al., 2005), whereas WSA does not range between four orders of magnitude for commercial ships (it ranged from 750 m^2 to 36,147 m^2 in this study). In addition, variation in organism density has been measured for BW in well replicated studies, ranging from <3000 organisms per m^3 but some had > 50,000 organisms per m^3 (Minton et al., 2005). The challenge remains to get similarly representative data for hull fouling across the commercial fleet.

Table 3. Ranks of vessel types in terms of West Coast arrivals, BW measures and WSA measures. Ship types were ranked, in order of most to least, according to the number of vessel arrivals (this study), mean BW discharge (Verling et al., 2005), number of discharging vessels and volume of BW discharged (from table 2, this study), mean and total WSA (this study).

vessel type	rank number of arrivals	rank mean BW discharge	rank number of discharging vessels	rank volume discharged	rank mean WSA	rank WSA delivered
auto carrier	4	6	5	6	4	4
barge	6	n/a	n/a	n/a	7	6
bulker	2	**1**	**1**	**1**	3	3
container	**1**	5	2	3	2	**1**
general cargo	7	4	6	5	6	7
unknown/other	8	3	7	7	8	8
passenger	5	7	3	4	5	5
tanker	3	2	4	2	**1**	2

West Coast shipping, transport geography, hull fouling & NIS risks

West Coast maritime shipping is dominated by containership traffic and this has major implications for the hull fouling vector of NIS. The combination of large vessels and many calls to port result in a more than 40% share of West Coast traffic, for both arrivals and WSA, dwarfing all other vessel types. Since its inception in the 1960s, containerization has steadily come to dominate maritime trade on a global scale and this has repercussions for the potential magnitude of species transfers to the West Coast - WSA arriving to West Coast ports is much greater for this vessel type than for any other. Determining if there is a relationship, however, between ship type and biofouling accumulation and accounting for variability across voyage routes, hull husbandry and other factors remains pivotal. Ballasting patterns have been shown to vary widely between ship types, even if ballast organism densities are independent of ship type because the mechanism of taking on ballast water does not vary between ship types. We have similarly shown the variation in aspects of hull fouling magnitude and frequency but the margin of variation between ship types does not appear as wide as it does for BW. The variation in organism density, however, may be wider for hull fouling than BW because of a possible direct link between ship type and the external nature of this vector (Davidson et al., in prep).

Containership traffic is also relevant to the hull fouling vector from the perspective of models of maritime trade routes. West Coast containership traffic fits the pendulum model of maritime transport geography with many vessels arriving to a major port after transoceanic voyages and stopping at other coastwise ports before returning to Asia (e.g. Asia - LA/Long Beach – Oakland – Tacoma – Vancouver BC – Asia). As economies of scale continue to drive vessel sizes upwards of the Panamax class (McCalla, 1999; Cullinane & Khanna, 2000), making the Panama Canal unsuitable for passage, we may expect the pendulum model will continue to grow in regularity as containerships, in particular, maximize their efficiency. This may have further repercussions for hull fouling transfers of species because of the potential biocidal effect that hulls are suspected to encounter as they pass through this hugely important bottle-neck of global shipping. Contrastingly, bulkers tended more toward the port-to-port model with relatively fewer repeat arrivals and more frequent calls to riverine ports than other vessel types, which may reduce the risk of introductions from this vessel type. River (or low salinity) systems have increased resistance to marine propagules that may reduce the numbers of invasions to freshwater-dominated ports from shipping (e.g. Smith et al., 1999; Davidson et al., 2006a).

Coastwise vessel movements between the three states accounted for one-third of the vessel traffic on the West Coast. This included almost all barge traffic and the coastwise legs of vessels with pendulum-type schedules. These vessel movements form strong linkages between Pacific coast ports (fig. 7), two-thirds of which receive and donate vessels from and to ten neighboring coastal ports. This is particularly relevant to secondary introductions that may result from hull fouling and BW. The connections make smaller ports that are not well connected to global ports susceptible to overseas NIS despite little overseas traffic. It is clearly significant in terms of LA/Long Beach, which is the most connected port in terms of donating vessels to other West Coast ports. Perhaps more important, however, are the linkages to San Francisco Bay's port system, which is the most invaded bay on the West Coast and whose ports are also connected ('upstream') to over 30 other West Coast ports. Not only does San Francisco Bay have the most known NIS but many NIS throughout other bays and harbors of the West Coast are also established in San Francisco Bay, many of which were first recorded there (Cohen et al., 1998; Sytsma et al., 2004). It may be that a hub and spoke model is at work for NIS on the West Coast, with San Francisco Bay as the hub and vessel movements to other West Coast ports acting as the spokes. BW management requirements by West Coast States is attempting to slow and ultimately prevent such movements and range increases of NIS; whether some similar efforts are needed or even possible for hull fouling remains to be assessed in the coming years.

Finally, there have been at least three major general components of shipping, relevant to the West Coast, which may have acted as inadvertent benefits to reducing species transfers and bioinvasions via hull fouling: 1) antifouling treatments 2) containerization, and 3) freshwater ports providing resistance. The potential for this vector to enable the spread of species has been well documented but these three, albeit inadvertent, preventative measures are also likely to have played an important reductive role in rates and extent of coastal marine introductions. Unlike BW organisms, hull fouling biota is costly to ships and antifouling reduces this cost with the additional benefit of reducing transfers of species. Only recently, studies of ship propulsion and antifouling efficiency cite the issue of NIS spread prevention as an additional benefit for effective approaches (Munk, 2006). Containerization and its effect of reducing port residence times (compared to break-bulk shipping that used to predominate [Vigarie, 1999]) may also reduce hull mediated NIS transfers by lessoning the time available for surface colonization by coastal species (Davidson et al., in prep). Freshwater ports are probably more resistant to NIS inoculation and probably have a lethal (and possibly purging) effect on marine hull fouling biota. Nonetheless, hull-mediated introductions have been well documented and direct measures of the effect of these three factors are lacking.

Summary, Research & Management Considerations

- Examining vessel traffic patterns and the magnitude of associated underwater wetted surface area (WSA) is a pivotal step in assessing the link between shipping, hull biofouling and potential species introductions relevant to regional spatial scales. We examined over 29,000 arrivals to the U. S. West Coast over a two-year period to assess how traffic and WSA varied according to ship type, arrival port, donor region, and arrival frequency.

- An estimated 265.6 million m^2 of WSA arrived to the West Coast, approximately half of which called on Californian ports. The dominant donor regions were in the NE and NW Pacific, and one-third of arrivals originated from coastwise voyages from within the three western states. Just 6% of arrivals were from outside of the Pacific Ocean.

- Variation by ship type in terms of mean WSA, total WSA and vessel arrival frequency plays an important role in characterizing traffic patterns and may be particularly relevant to an external shipping vector. Containerships dominated total WSA arrivals but were heavily associated with just seven ports.

- Containerships appeared to follow the pendulum model of maritime transport geography, with many vessels calling to LA/Long Beach after a transoceanic voyage and departing for coastwise ports prior to a returning transoceanic voyage. Incorporating trade and transport geography models is useful for characterizing traffic and WSA flux, and especially for predicting the future patterns and effects that trade may have on new NIS establishment (e.g. Levine & D'Antonio, 2003).

- West Coast ports are well connected to each other in terms of donating and receiving vessels to and from each other. This has repercussions for hull-mediated secondary spread of species along the West Coast, and may be particularly relevant for ports that are 'downstream' of highly invaded harbors.

- Although we have quantified WSA and vessel traffic flux on the West Coast, biological interpretation of these trends, related to the hull fouling vector and NIS risk, requires additional biological data that does not presently exist. Gathering these data on biofouling density of vessels representative of the commercial fleet is clearly a priority. The effects of voyage speeds, port durations, arrival frequency, voyage patterns and hull husbandry regimes within and among ship types are needed to determine the extent of fouling on ships and the relative importance of each of these factors. The issue of species identity (NIS or native) may be secondary as these data are gathered. For example, over a two year period a majority of bulkers tended to arrive to West Coast ports just once or twice from overseas, so their associated biofouling assemblage is likely to be non-native because the great majority of their time is not spent in West Coast waters. Gathering data at species level resolution should not be a priority if it acts to delay, or prevent because of expense, the collection of density (% cover) data.

- Further data from vessel arrivals relating to antifouling use, port durations, lay-up times and dry docking intervals are required to further determine variation within and among ship types across the commercial fleet (Takata et al., 2006). When combined with WSA and traffic flux data, they will provide measures of vessel management and behavior across the fleet, which is currently unavailable.

- Other hull fouling related research requirements that will inform management decisions include: 1) new and continued surveys of bays and harbors to document NIS populations, NIS range sizes, new NIS incursions and rates of successful transfers. If BW management is effective, it will be important to ascertain whether fewer introductions occur and if hull-mediated introductions become relatively more prevalent (Fofonoff et al., 2003); 2) experiments on the effect of environmental variability (temperature and salinity) on fouling organism quality; 3) experiments on how organisms can colonize a new area (‘jump ship’). At present it is thought that spawning events are the main mechanism (Minchin & Gollasch, 2003), but there is no data on the frequency of this occurrence across taxa. For the BW vector, organisms are released directly to the ecosystem but fouling organisms act independently of ship operations to release themselves or their next generation into the receiving waters.

- Although we have shown numerous differences between ship types in various aspects relevant to the magnitude of the hull fouling vector, the management repercussions remain unclear. Regulatory action to ensure regular maintenance of vessels combined with technological advances in antifouling and hull husbandry techniques form the basis of a framework, but representative data are currently lacking which makes specific actionable management difficult. In addition, given that BW regulation and management occurs regardless of ship type, specific trends related to ship type might have no bearing on future management considerations for hull fouling as well. If, however, hull fouling accumulation and vessel behavior (related to ship type) are shown to be linked, this may provide the basis of a ranking of risk level for different ships prior to their arrival in coastal waters of a state or port. Also, if aspects such as the forthcoming ban on TBT paints make an important difference to the extent of fouling and rates of species transfers on ships, the behaviors of certain ship types that lend themselves to fouling accumulation may have to be examined.

- Managing stochastic shipping events that focus on extremely high-density biofouling has been the focus of management efforts thus far throughout the world (e.g. Brock et al., 1999; Coutts, 2005; Godwin, 2005b; Davidson et al., 2006a). Although this is clearly necessary given the importance of initial inoculant size to the probability of establishment, this approach accounts for less than 1% of vessel arrivals, and it is important to consider the other aspects of propagule supply such as magnitude, frequency, and duration. The challenge remains to improve our understanding of biofouling on commercial vessels representative of the fleet. If management is then deemed necessary, the best information can be made available to ship operators and decision-makers to ensure introductions do not continue as a major side-effect of maritime trade.

References

Apte S, Holland BS, Godwin, LS, Gardner, JPA (2000) Jumping ship: a stepping stone event mediating transfer of a non-indigenous species via a potentially unsuitable environment. Biological Invasions. 2: 75-79.

Barsness RW (1997) Maritime activity and port development in the United States since 1900: a survey. In: Williams DM (ed) The world of shipping. Ashgate Publishing Ltd. Aldershot, England. pp 115-132.

Brock RE, Bailey-Brock JH, Goody JH. (1999) A case study of efficacy of freshwater immersion in controlling introduction of alien marine fouling communities. Pacific Science 53(3): 232-231.

Carlton JT (1985) Transoceanic and interoceanic dispersal of coastal marine organisms: The biology of ballast water. Oceanography and Marine Biology Annual Review. 23: 313-371.

Carlton JT, Geller JB (1993) Ecological roulette: the global transport of nonindigenous marine organisms. Science. 261: 78-82.

Clarke KR, Warwick RM (2001) Change in marine communities: an approach to statistical analysis and interpretation, 2nd edition. Plymouth: PRIMER-E.

Cohen AN, Berry HK, Wonham MJ, Cordell J, Milne D, Secord D, Bingham B, Bookheim B, Chapman JW, Harris LH, Kohn A, Li K, Mills CE, Mumford T, Radishevsky V, Sewell A. (2000) Report of the Washington State exotics expedition: A rapid assessment survey of exotic species in Elliot Bay, Totten/Eld Inlets and Willapa Bay. Washington State Department of Natural Resources, Olympia WA.

Cohen AN, Carlton JT (1995) Nonindigenous Aquatic species in a United States Estuary: A case study of the biological invasions of the San Francisco Bay and Delta. U. S. Fish and Wildlife Service, Washington DC.

Cohen AN, Carlton JT (1998) Accelerating invasion rate in a highly invaded estuary. Science. 279: 555-558.

Cohen AN, Harris LH, Bingham BL, Carlton JT, & 7 other authors (2002) Project report for the southern California exotics expedition: A rapid assessment survey of exotic species in sheltered coastal waters. California Department of Fish & Game. Sacramento, California.

Cohen AN, Mills CE, Berry H, Wonham MJ & 12 other authors (1998) A rapid assessment survey of nonindigenous species in the shallow waters of Puget Sound. Nearshore Habitat Program, Washington State Department of Natural Resources. Olympia, Washington.

Cordell JR, Morrison SM (1996). The invasive Asian Copepod *Pseudodiaptomus inopinus* in Oregon, Washington, an British Columbia Estuaries. Estuaries. 19: 629-638.

Coutts ADM. (2005) Slow-moving barge introduces biosecurity risk to the Marlborough Sounds, New Zealand. In: Godwin LS (ed) Hull fouling as a mechanism for invasive species introductions. Proceedings of a workshop on current issues and management strategies, February 12-13, 2003. Honolulu, Hawaii. pp 29-36.

Coutts ADM, Taylor MD (2004) A preliminary investigation of biosecurity risks associated with biofouling on merchant vessels in New Zealand. New Zealand Journal of Marine and Freshwater Research. 38: 215-229.

Cullinane K, Khanna M (2000) Economies of scale in large containerships: optimal size and geographical implications. Journal of Transport Geography. 8: 181-195.

Davidson I, Ruiz G, Sytsma G (in prep) The influence of ship type and behavior on characteristics of a marine invasive species vector: commercial vessel hull biofouling.

Davidson I, Sytsma M, Ruiz G (2006a) Preliminary investigations of biofouling of ships' hulls: Non-indigenous species investigations in the Columbia River. U. S. Coast Guard Research & Development Center. Groton, Connecticut.

Davidson I, Ruiz G, Sytsma M, Fofonoff P (2006b) Hull biofouling on the vessels POINT LOMA and FLORENCE in the Reserve Fleet at Suisun Bay, CA: A pilot study with respect to potential transfer of non-native species. U. S. Maritime Administration, Washington D.C.

Drake JM, Lodge DM (2004) Global hot spots of biological invasions: evaluating options for ballast-water management. Proceedings of the Royal Society of London B. 271: 575-580.

Drake JM, Lodge DM (2006) Allee effects, propagule pressure and the probability of establishment: risk analysis for biological invasions. Biological Invasions. 8: 365-375.

Eno CN, Clark RA, Sanderson WG (1997) Non-native marine species in British waters: a review and directory. Joint Nature Conservation Committee. Peterborough, England.

Falkner M, Takata L, Gilmore S (2005) Report on the California marine invasive species program. Prepared for the California State Legislature by the California State Lands Commission. Sacramento, California.

Feyrer F, Herbold B, Matern SA, Moyle P (2003) Dietary shifts in a stressed fish assemblage: consequences of a bivalve invasion in the San Francisco estuary. Environmental Biology of Fishes. 67: 277-288.

Fofonoff PW, Ruiz GM, Steves B, Carlton JT. (2003) In ships or on ships? Mechanisms of transfer and invasion for nonnative species to the coasts of North America. In: Ruiz GM & Carlton JT (eds) Invasive species: vectors and management strategies. Island Press. Washington DC. pp. 152-182.

Godwin LS (2005a) Hull fouling as a mechanism for invasive species introductions. Proceedings of a workshop on current issues and management strategies, February 12-13, 2003. Honolulu, Hawaii.

Godwin LS (2005b) Development of an initial framework for the management of hull fouling as a marine invasive species transport mechanism. In: Godwin LS (ed) Hull fouling as a mechanism for invasive species introductions. Proceedings of a workshop on current issues and management strategies, February 12-13, 2003. Honolulu, Hawaii. pp 29-36.

Gollasch S (2002) The importance of ship hull fouling as a vector of species introductions into the North Sea. Biofouling. (18): 105-121.

Grevstad FS (1999) Factors influencing the chances of population establishment: Implications for release strategies in biocontrol. Ecological Applications. 9: 1439-1447.

Helling A, Poister TH (2000) U. S. Maritime ports: Trends, policy, implications, and research needs. Economic Development Quarterly. 14: 300-315.

Hewitt C, Gollasch S, Minchin D (in press) The vessel as a vector – biofouling, ballast water and sediments. In: Rilov G, Crooks J (eds) Marine bioinvasions.

Hewitt CL, Campbell ML, Thresher RE, Martin RB, Boyd S, Cohen BF, Currie DR, Gomon MF, Keough MJ, Lewis JA, Lockett MM, Mays N, MacArthur MA, O'Hara TD, Poore GCB, Ross DJ, Storey MJ, Watson JE, Wilson RS. (2004) Introduced and cryptogenic species in Port Philip Bay, Victoria, Australia. Marine Biology 144: 183-202.

Levine JM, D'Antonio (2003) Forecasting biological invasions with increasing international trade. Conservation Biology. 17: 322-326.

Lewis EV (1988) Principles of Naval Architecture. Jersey City, New Jersey: The Society of Naval Architects and Engineers.

Maritime Administration (2004) Draft summary of the MARAD 3rd Annual short sea shipping conference, October 13-15, 2004. Maritime Administration, Washington D.C. http://www.marad.dot.gov/sss/research/index.asp

Maritime Administration (2006) U.S. Port Calls by Port and Vessel Type, 2002-2005. Maritime Administration, Washington. D.C. http://www.marad.dot.gov/MARAD_statistics/index.html

McCalla RJ (1999) From St. John's to Miami: Containerisation at Eastern Seaboard Ports. Geojournal. 48: 21-28.

Minchin D, Gollasch S. (2003) Fouling and ships hulls: how changing circumstances and spawning events may result in the spread of exotic species. Biofouling 19: 111-122.

Minton MS, Verling E, Miller AW, & Ruiz GM (2005) Reducing propagule supply and coastal invasions via ships: effects of emerging strategies. Frontiers in Ecology and the Environment. 3: 304-308.

Munk T (2006) Fuel conservation through managing hull resistance. Propulsion Dynamics Inc. A paper presented at the Motorship Propulsion Conference, Copenhagen, April 26th, 2006.

Nichols FH, Thompson JK, Schemel L (1990) Remarkable invasion of San Francisco Bay by the Asian clam *Potamocorbula amurensis* II. Displacement of a former community. Marine Ecology Progress Series. 66: 95-101.

Niimi AJ (2004) Role of container vessels in the introduction of exotic species. Marine Pollution Bulletin. 49: 778-782.

Ricciardi A (2001) Facilitative interactions among aquatic invaders: is an "invasional meltdown" occurring in the Great Lakes? Canadian Journal of Fisheries and Aquatic Science. 58: 2513-2525.

Richman SE, Lovvorn JR. (2004) Relative foraging value to lesser scaup ducks of native and exotic clams from San Francisco Bay. Ecological Applications 14(4): 1217-1231.

Roberts L (1990) Zebra mussel invasion threatens U. S. waters. Science. 249: 1370-1372.

Rodrigue J-P, Comtois C, Slack B (2006) The Geography of Transport Systems. Hofstra University, Department of Economics & Geography. http://people.hofstra.edu/geotrans.

Ruiz GM, Brown C, Smith G, Morrison B, Ockrassa D, Nekinaken K (2004) Analysis of biofouling associated with the hulls of containerships arriving to the Port of Oakland: a pilot study. In: Ruiz, GM, Smith G. Biological studies of containerships arriving to the Port of Oakland. Oakland, California. pp 138-155.

Ruiz GM, Fofonoff PW, Carlton JT, Wonham MJ, Hines AH. (2000) Invasion of coastal marine communities in North America: Apparent patterns, processes and biases. Annual Review of Ecology and Systematics 31: 481-531.

Simkanin C, Sytsma M (2006) Oregon ballast water task force report on ballast water management in Oregon. Prepared for the Oregon State Legislature. Salem, Oregon.

Smith LD, Wonham MJ, McCann LD, Ruiz GM, Hines AH, Carlton JT (1999) Invasion pressure to a ballast-flooded estuary and an assessment of inoculant survival. Biological Invasions. 1: 67-87.

Sytsma MD, Cordell JR, Chapman JW, Draheim RC. (2004) Lower Columbia River aquatic nonindigenous species survey 2001-2004 Final Technical Report: Appendices. Prepared for the United States Coast Guard and the United States Fish and Wildlife Service. Portland OR.

Takata L, Falkner M, Gilmore S (2006) Commercial vessel fouling in California: Analysis, evaluation, and recommendations to reduce nonindigenous species release form the non-ballast water vector. California State Lands Commission. Marine Facilities Division. Sacramento, California.

Van Maanen JD, Van Oossanen P (1988) Resistance. In: Lewis EV (ed) Principles of Naval Architecture, Volume II. Jersey City, New Jersey: The Society of Naval Architects and Engineers. pp 1-93.

Verling E., Ruiz GM, Smith LD, Galil B, Miller AW, Murphy K (2005). Supply-side invasion ecology: characterizing propagule pressure in coastal ecosystems. Proceedings of the Royal Society of London B. 272: 1249-1256.

Vigarie A (1999) From break-bulk to containers: the transformation of general cargo handling and trade. Geojournal. 48: 3-7.

Wonham MJ, Carlton JT. (2005) Trends in marine biological invasions at local and regional scales: the Northeast Pacific Ocean as a model system. Biological Invasions 7: 369-392.